Chalmers University of Technology

Solar Energy - from Photons to Future Societal Impact

Agrivoltaics in Sweden

Group 2

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Agrivoltaics in Sweden, Törneby solpark, photo by Kalmar Energi [1]

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Abstract

This report examines the integration of renewable energy into agriculture, focusing on agrivoltaic systems (APVs) that combine photovoltaic (PV) energy generation with farming. It compares Conventional Ground-Mounted Photovoltaics (CGMPVs) and Vertical Bifacial Photovoltaics (VBFPVs) to assess their economic viability and production potential. Additionally, it explores the implications and social acceptance of PV integration in Swedish agriculture, including land-use efficiency, food security, and market dynamics, offering insights for stakeholders seeking sustainable energy solutions in farming.

1 Introduction

Agrivoltaics in Sweden is explored in this report through a literature review (Section 2), followed by two main approaches: a qualitative assessment capturing farmers' perspectives through interviews and a quantitative assessment modelling a hypothetical APV system based on these insights. The findings are integrated in the discussion (Section 5) and summarized in the conclusion (Section 6).

1.1 Motivation

In the light of the ever increasing demand for sustainable energy production photovoltaics present an economically viable and easily accessible technology that helps meet this demand. Though the energy demands are rather easily met with photovoltaics the high land demand of this technology clashes with other land uses. One of the land types most endangered by photovoltaic power production is agricultural land which is a valuable and scarce land type in many countries. Between 1951 and 2010 Sweden, as the country of interest for this study, has lost over 1 million hectares of arable land, equal to 28% of the total, and in the last 15 year the total agricultural land further decreased by 80,000 hectares [2][3]. In an economy that is already mostly dependant on the foreign import of food, further reduction of ones own production is not desirable. Additionally, on a global scale a decrease of food production capacity clashes with the Sustainable Development Goal 2 *No Hunger* set by the United Nations [4]. Therefore, a solution that effectively combines agriculture and photovoltaics while meeting both the food and energy needs is desirable. Thus, this report explores and discusses the topic of agrivoltaics and their application in Sweden.

1.2 Research Aim and Objectives

The research questions of the project are:

- *What are the benefits of implementing agrivoltaic systems for both the Swedish farmers and the electricity system?*
- *Is it feasible to implement it on a large scale?*
- *What are the farmers point of view regarding the matter?*

2 Literature review

In this section, a literature review is provided, beginning with the definition of agrivoltaics, followed by technological considerations and an overview of Sweden's agricultural conditions. Next, the impact of agrivoltaic systems on farming is examined, exploring then the ethical considerations of agrivoltaic systems and farming, followed by an overview of the current Swedish regulatory framework governing APV installations. Finally, the installations currently present within these conditions are presented.

2.1 What is agrivoltaics?

The concept of agrivoltaics encompasses every activity that involves the dual use of land for both agriculture and power production through photovoltaic technology. The area of interest of this topic is very broad and the extent of what constitutes agrivoltaics is mutable.

There are different classifications of APVs, such as different types of agriculture the panels are sharing the land with or different ways to arrange the modules, which are further explained in subsection 2.2. The common denominator for all APV systems is that the arrangement and design of the panels are optimized to balance the energy needs of solar power generation and the growth conditions required by the agricultural activity. Although the first agrivoltaic installations date back to the early 1980s, the topic only began to attract widespread attention about ten years ago [5].

The reasons for this renovated interest can be traced back to a more profound awareness of climate change as well as a technological development of solar PVs [5]. The growing urgency to combat climate change has intensified the efforts to transition from fossil fuels to renewable energy sources, while the development of photovoltaic technology enables more creative and adaptable ways of implementing the technology. Additionally, the strive towards a more sustainable use of land has stimulated the search for different solutions and one of these is the concept of agrivoltaics. Recent studies have demonstrated the ability of APV systems to increase land-use efficiency while maintaining a high crop yield [5]. Countries such as Japan, Germany and the United States have been frontrunners in the implementation of these systems, showcasing their viability in both developed and developing regions [5].

2.2 Technological considerations

Agrivoltaic installations highly depend on the activities that are carried out in combination with the photovoltaic production, such as agricultural production in fields or in greenhouses, livestock rearing, provision of ecosystem services or multiple of these practices combined, as in Figure 1.

Moreover, the nature of the installation is determined by the approach followed:

- energy production approach, focused on optimizing the solar energy produced
- agricultural production approach, focused on optimizing the crop production
- integrated agricultural and energy production approach, trying to incorporate both uses into the system design in the most beneficial manner possible

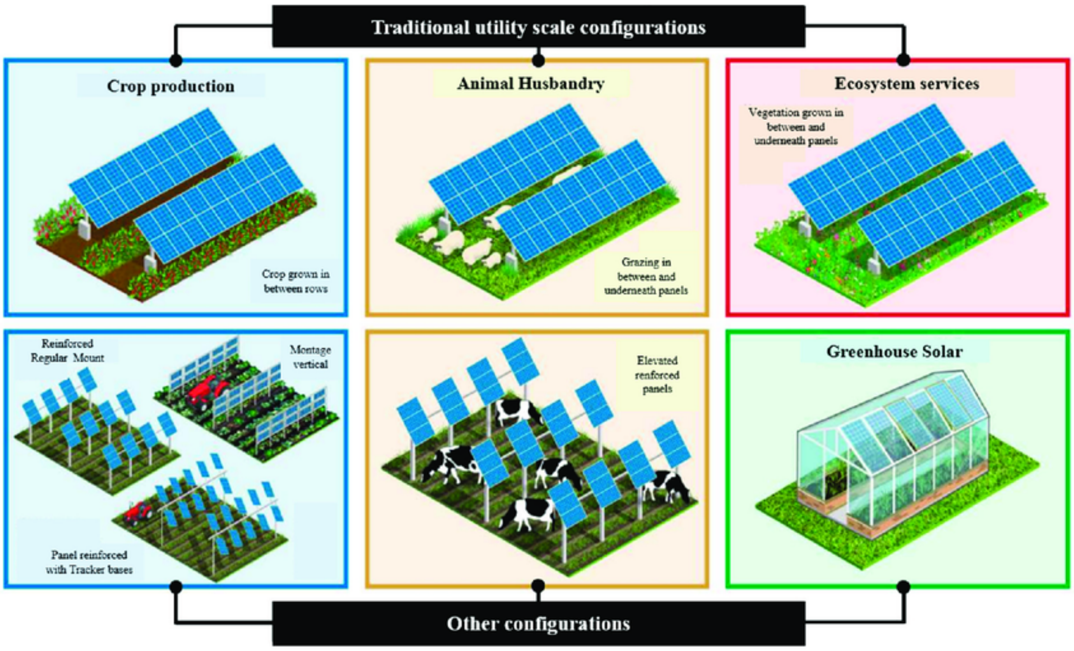


Figure 1: *Different agrivoltaics system configurations [6]*

Traditional utility scale PV plants, referred to in this report also as Conventional Ground-Mounted Photovoltaics (CGMPVs), can be integrated with agricultural activities as they are, creating an environment which is already suitable for grass cultivation, sheep grazing and ecosystem services. However, to improve the crop yield, they can be adapted to the needs of agricultural land use with two different types of module configuration: interspace (or *inter-rows*) and overhead (or *elevated*) [6].

Interspace systems have a similar arrangement to traditional installations, with considerable space between consecutive rows of panels in order to facilitate the movement of large agricultural machinery. The investment cost necessary for this type of installation is low, but the uncultivated space below the panels can lead to a reduction in crop yield [6]. The interspace configuration is mostly used for the cultivation of lower-value crops, such as grasses, grains and hardy vegetables as well as sheep grazing [7].

Overhead systems, on the other hand, have PV modules installed at minimum 1.8 m above the ground and agricultural activity is carried out below the panels. This configuration has higher investment and maintenance costs, but the crop yield is increased, due to the space availability, and it is common to cultivate higher-value crops, such as berries, grapes, short-stature fruit trees and delicate vegetables, or put cattle to graze [7]. The elevated PV panels can grant protection from harsh weather condition, but substantially reduce the exposure of the crops to sunlight.

Therefore, multiple studies have been conducted on the elevation and spacing of solar PV modules in order to maximize energy and agricultural production [7][8]. Although the minimum height for overhead PVs is often found to be 1.8 m, installations above 2.4 m are preferable for crops and some configurations reach up to 5.2 m, since a higher elevation of the modules favours a more even distribution of sunlight and allows the movement of equipment and people under the panels [7][8].

When it comes to the spacing of the panels, the traditional utility scale installations require only a minimum distance between the PV rows that allows them to not shade each other. For overhead APVs, the space between rows can also be opened up, with similar benefits to interspace systems. Additionally the PV modules in a single row can be spaced further apart to reduce the shading of the crops further. In multiple previous studies the spacing tested in the field ranged from 0.71 m to 9.5 m, between rows, and from 0.2 m to 6.4 m, between panels [9][10][7][11].

Other than with module spacing, better performances of elevated agrivoltaics systems can be reached with optimal tilt angle and orientation of the PVs, which increase the yield of both energy generation and crops. For fixed installations, various tilts and orientations are tested and strongly depend on the location.

However, the solution that grants the most flexibility in the light management under the panels is the implementation of solar tracking modules [12]. Tracking PV systems benefit from a mechanical system that can adjust tilt and orientation of the modules at different times of the day in order to optimise the energy production and can be of two types: single-axis and double-axis trackers. In the first case, the sun is tracked either horizontally, according to its angle of incidence, or vertically, according to its orbit. In the second case, instead, the system is able to combine the two, making it more effective in terms of energy production. The large structure with flexible tilt grants also constructive protection from hail and extreme radiation, but can also cause irregular distribution of light on the crops and comes with high investment and maintenance costs. As PV panel prices have decreased, the relative cost of implementing tilted structures has become comparatively higher [13].

Lastly, agrivoltaics systems can be built by mounting the PVs vertically. Since these systems require large inter-row spacing to avoid shading each other, using the land in between for agricultural purpose is an efficient solution. The crops yield is increased by larger distances between the rows of panels, up to 50% less in the case of 5 m compared to 20 m [14]. The distribution of sunlight and rainwater on the crops is not affected by this configuration and the human activities, like the movement of farm machinery and the panels maintenance, are favoured. This type of installations usually require bifacial panels, in order to maximise the energy yield, with an orientation that depends on the approach followed: east-west when the focus is on permanent crops, north-south for better energy production [6]. Vertical Bifacial Photovoltaics (VBFPVs) are more economical than overhead systems due to the lower support costs [15].

A helpful parameter for the comparison of different APV systems is the Land Equivalence Ratio (LER), which measures the land use efficiency of agrivoltaics and is calculated as a function of the area of the PV system and the total area needed to meet the agricultural and electricity production of the system, as in Equation 1.

$$LER = \frac{yield_{crop}(dual)}{yield_{crop}(mono)} + \frac{yield_{el}(dual)}{yield_{el}(mono)} \tag{1}$$

2.3 Agricultural conditions in Sweden

Swedish farmers work under nordic climate conditions. Only about 6.5% of Sweden's land area is used for agriculture, and significant variations exist between the northern and southern regions [16]. For instance, the growing season in southern Sweden lasts about 100 days longer compared to the north [16]. Thanks to these more favourable climate conditions and fertile soils, southern regions such as Skåne, Västra Götaland and Östergötland are the country's agricultural hubs.

Dairy and bovine meat represent approximately one-third of the agricultural sector's production value, while crop production accounts for about 40%. The remaining 30% is divided between pig farming, poultry, and horticulture. Among the crops grown in Sweden, cereals such as barley, oats and wheat are the most common, comprising 40% of total crop production. Yields of the commonly grown crops like cereals are comparable to other high-performing European agricultural regions, with wheat averaging around 7-8 tons per hectare, while barley and oats yield approximately 5-6 tons per hectare under optimal conditions [17]. Grasslands are also a significant feature of Swedish agriculture, covering 34% of the total agricultural land [16]. Over time, Swedish agriculture has shifted from small-scale farming with many workers to larger, mechanized farms employing fewer people [16]. Advances in technology, such as pesticides and fertilizers, have increased yields but have also contributed to biodiversity loss [16].

2.4 Effect on agriculture

Solar panels cause shading on the crops that can alter the microclimate and impact factors such as light availability, temperature and soil moisture. This side effect, however, can also be beneficial for the crops, reducing heat stress and water evaporation. This section explores how agrivoltaics affects crop yield and livestock farming, highlighting both the potential benefits and challenges of this innovative dual-use system.

2.4.1 Cultivation of crops

It has been shown that strategic shading and improved water retention can benefit certain crops, especially during periods of heat stress. A particular example are bell peppers (Capsicum anuun L.). A previous study on the topic saw an improvement in photosynthetic efficiency and increase in yield at 50% which compares to the amount of shading achieved in a VBFPV installation [18]. On the other hand, it has been shown that shading can also decrease the crop yield by between 5 and 20% relative to open farmland depending on the crop cultivated [19].

Livestock grazing heavily depends on the herbage yield of pastures, where the estimation of typical herbage yield is believed to be around 7 to 10 tons of dry matter per hectare annually [20]. It mostly depends on soil fertility, grazing practices, use of fertilizers and climate conditions. When it comes to implementing VBFPVs, there is a decrease in terms of herbage yield which might vary from 0% to 33% [21].

2.4.2 Agricultural livestock

The combination of photovoltaics with animal farming can be very diverse, to the extent of including rabbits, fishes and even emus. However, one of the most common and mature livestock production when combined with photovoltaic electricity production is lamb or sheep. Even though pastures with APV systems can have up to 33% lower herbage than conventional pastures, this is balanced by a higher forage quality.

Sweden has a population of approximate 250,000 sheep [22]. An important information to acknowledge is the number of sheep one can keep per hectare of land. That data is very much case dependant but one can try to identify patterns. In southern Sweden, regarding the current herbage yields, it is common to graze about 4 to 6 sheep per hectare in natural land and up to 20 on cultivated agricultural land [23]. Even though the number of studies conducted to investigate the livestock production in APV systems is limited, it is believed that this value may hardly be impacted by the VBFPV [21].

2.5 Ethical considerations

Agrivoltaic systems are at the nexus of land, food and energy, closely linked to Sustainable Development Goals (SDGs) of *Zero Hunger* (SDG 2), *Affordable and Clean Energy* (SDG 7) and *Combat Climate Change* (SDG 13) [4]. Moreover, the need for agricultural land is expected to increase by up to 50% by 2050 due to growing demand for bioenergy [24]. This global rise in demand contrasts with the ongoing decline in arable land availability, further intensifying land competition [24].

By reducing land competition, APV systems enable the simultaneous production of food and renewable energy, addressing critical global challenges. This dual use not only enhances resource efficiency but also aligns with ethical consideration to ensure equitable access to essential resources like food and clean energy while mitigating climate change. However, dual use of land can also create conflicts about what to prioritise, which raises ethical concerns. As renewable energy generation demands more area compared to fossil conventional power plants the competition for land is plausible to increase [25].

The power density of solar PV varies depending on the metric used. Gross power density, based on the active panel area, typically ranges between 150–200 W/m^2 [26]. However, the net power density of utility-scale solar farms, which accounts for the total land area occupied, falls between 2–10 W/m^2 due to spacing to avoid shading etc [25]. In contrast, fossil fuel plants achieve a gross power density of 200–11,000 W/m^2, as their power generation facilities are highly concentrated [25].

The comparison becomes less straightforward when considering the land required for extracting and transporting fossil fuels, making it challenging to evaluate the numbers in a fair and consistent way. Thus, it is important to acknowledge that the integration of solar energy and agriculture requires careful consideration to ensure that neither food security nor energy goals are compromised [25]. Studies highlight the need for strategies that optimize land-use efficiency while minimizing adverse effects on agricultural yields, such as using shade-tolerant crops or adjustable PV panels [27].

2.6 Regulatory framework

Sweden's Environmental Code[1] emphasises the preservation of productive agricultural and forestry lands as resources of national importance [28]. According to Chapter 3 Section 4, valuable agricultural land can only be repurposed for development if essential societal interests, such as energy infrastructure, cannot be met using less valuable land [29]. Valuable agricultural land includes both arable land and pasture. An additional requirement is stipulated in Chapter 3, Section 1, which states that land must be used

[1] Miljöbalken

for the most suitable purpose. Priority should be given to uses that are considered good management from a public perspective. This can, for example, include not only agricultural use but also an investigation into whether other energy sources, such as wind power, might be more suitable for the area.

Large-scale solar parks typically require consultation under the Environmental Code due to their potential impact on natural environments [30]. The County Administrative Board oversees regulatory processes for ground-mounted solar installations. This includes whether the installation complies with laws, such as those protecting agricultural land or natural values. They have discussions with different stakeholders, including nearby residents and the board itself, to provide the opportunity to give feedback on the project. While building permits are not required for panels, associated infrastructure like transformer stations does, which are handled by the municipality [31].

2.7 Current agrivoltaic installations

Globally there are several agrivoltaic installations either with simultaneous crop cultivation or grazing of livestock. However, as pointed out in subsection 2.3, Sweden is characterised by a Nordic climate and thus also by a low yearly insolation, between 950 and 1130 kWh/m^2 on average, whereas at lower latitudes, like Sub-Saharan Africa, it is higher than 2300 kWh/m^2 [32]. As a consequence not many agrivoltaic installations are located in Sweden, but are rather found in countries and regions with high insolation, due to their particularly heavy dependence on the abundance of solar irradiation to satisfy both of the uses they combine.

There seems to be change on the horizon, though, since in the last few years more and more research has been conducted on the topic, as well as the first commercial agrivoltaic installations have been built. Currently the biggest installation is built and operated by Svea Solar in cooperation with Ekoväx on a site near Mariestad. It has a prospective electricity generation of 8 GWh/year [33]. The high energy production achieved is due to the installation using an overhead tracking system.

Other notable sites in Sweden include two research sites by Mälardalen University in Kärrbo and Vässlingby. The installation near Kärrbo is a research installation with 11.8 kWp of south-facing fixed tilt panels and 22.8 kWp of east-west facing vertical bifacial panels [34]. Solvallen, near Vässlingby, is a pure VBFPV site with an installed peak power of 635 kWp over an area of 1 ha [35].

All three sites so far have been combining photovoltaics with crop growth. Installations combining photovoltaics and livestock grazing, namely sheep grazing, are more common. Such facilities are either planned with sheep grazing in mind or sheep are integrated later and used to replace the need to mow the grass between the panels. These type of systems include installations in Forsby, Sjöbo, Åhus. A more extensive list, originally compiled by Bengt Stridh and expanded by the authors of this report can be found in Appendix A. There is no record of VBFPV installations combined with sheep grazing in Sweden.

2.8 Key Findings of the literature review

That a change towards more sustainable alternatives in human power generation is needed has been proven plenty in various studies. As shown, agrivoltaics is a technology that enables such a change. Though, keeping in mind the ethical considerations and the boundaries of the agricultural conditions present in Sweden, agrivoltaics also present challenges. The high variability in sunlight makes supporting both agriculture and photovoltaics a challenge. This makes innovative designs necessary to optimize the energy generation without negatively impacting crop yields. These emerging technologies may even be beneficial for stakeholders as Vertical Bifacial panels and their characteristic double peak production profile show. Additionally, careful planning will be critical to ensure the long-term sustainability of agrivoltaics when considering the current and future land-use pressures.

3 Methodology

To address the research questions, two main approaches are used. To examine farmers' perspectives on the matter, five interviews is conducted with individuals currently or formerly working in the agricultural sector. To assess the technical feasibility and the impact on the electricity system, a quantitative assessment is done of an hypothetical APV system using three different scenarios as well as a reference scenario.

3.1 Qualitative Assessment of Farmers' Perspective

To gain insights into the perspectives of farmers regarding agrivoltaic systems, semi-structured interviews are conducted with five participants who are either currently or formerly engaged in the agricultural sector. This approach is chosen to allow for both consistency across interviews and flexibility to explore unique insights shared by participants. The results of the interviews are also highly connected to the formation of the hypothetical APV system in the quantitative assessment.

The interviews are semi-structured, guided by a set of questions designed to explore the farmers' view both on the concept of agrivoltaics and its feasibility within the sector. Some of the interviewed people already have or are planning for solar farms on their land, then questions regarding the installation are asked as well.

3.1.1 Data collection

Interviews are conducted over phone, video meeting, or in person, lasting approximately 30 minutes each. All participants agree on their answers being used in this report. The following questions were asked:

- What type of farming do you practice?
- What is your general opinion of solar panels, both large-scale and small-scale?
- What do you think of agrivoltaics?
- When do you think agrivoltaics have the biggest potential?
- What type of agrivolatics would be most suitable for your type of agriculture?

Additional questions are included during the interviews to qualify the responses and ensure a deeper understanding of their perspectives.

3.1.2 Data analysis

The interview data is analysed qualitatively to identify common themes, insights, and perspectives shared by participants. Responses were systematically reviewed to extract key viewpoints regarding the feasibility, potential, and challenges of implementing agrivoltaic systems in agricultural settings. Particular attention is paid to practical considerations, such as land use, if they have PV installations or plans for it, and the integration of solar panels with existing farming practices.

3.2 Quantitative Assessment of an APV System

In order to assess the technical and economical feasibility and the impact on the electricity system of APV systems, a model is developed using spreadsheet. The model consists in a hypothetical APV system, combining sheep grazing with different PV configurations, with the assessment of electricity production and profits in three different scenarios, together with a reference case.

The type of PV installations investigated are:

- conventional ground-mounted panels (CGMPVs), south oriented;
- vertical bifacial panels (VBFPVs), east-west oriented.

The CGMPV installation is composed of panels typically installed in utility-scale PV farms, set on a tilt of 45° and with a specific capacity of 100 W/m^2. After the installation of these panels, it is still possible to cultivate grass and graze sheep, with a herd size estimated to be 40% of the one present on the land in its original configuration. The land utilisation is large, reducing considerably the agricultural yield and making this case more suitable for an approach focused on the energy production. On the other hand, the VBFPVs are a type of installation that, due to its disposition and its requirement for inter-row spacing, occupies a very small percentage of the land and leaves sheep grazing conditions almost unaffected.

Data from the simulation tool PVGIS was used as input values for the model. PVGIS uses data from ERA5 database which is a global climate dataset from ECMWF[2], offering hourly weather and climate data with high spatial resolution from 1950 to the present [36].

The area investigated is assumed to be originally cultivated agricultural land, which can support up to 20 sheep per hectare [23], and the yearly revenue per sheep is estimated to be 1,300 SEK/year/sheep. The derivation of this figure is shown in Appendix B and the value is also confirmed by farmers in the interviews.

The model considers an agricultural land area of 10 hectares located at 59°00’00”N 15°00’00”E, referenced as *Örebro*, near the geographical centre of the electricity market bidding area SE3.

Different scenarios are run in the model to get an insight on the profitability of sheep farming on PV land. The different scenarios are the following, also illustrated in Figure 2:

- **Scenario 0** reference case, where 100% of the land is used for sheep farming and no PVs are installed.
- **Scenario 1** installation of CGMPVs over the entire land, with sheep grazing reduced by 60%, according to previous estimations.
- **Scenario 2** installation of VBFPVs in combination with sheep farming over the entire land.
- **Scenario 3** installation of CGMPVs over the entire land and discontinuation of the sheep grazing.

[2]European Centre for Medium-Range Weather Forcasts

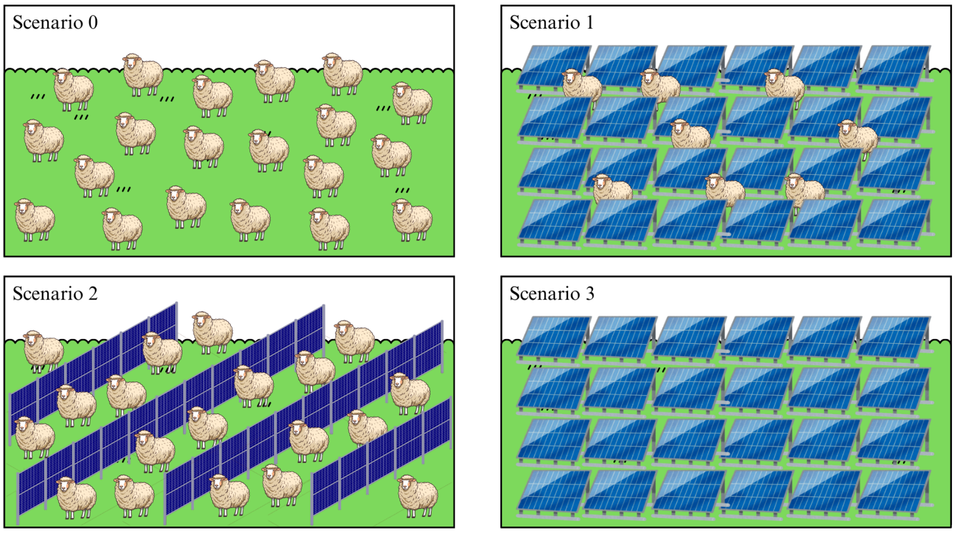


Figure 2: *Illustration of the four analysed scenarios*

The comparison between the four scenarios is based on the total profit, as derived from the Excel model. A detailed explanation of the model can be found in Appendix C. The LER, mentioned in subsection 2.2, is also calculated for all the scenarios.

The hourly electricity production profile over one year is generated for both CGMPVs and VBFPVs, thanks to the data from PVGIS, and the production per kWp installed of the two is compared. Also, so as to compare the models, the average production per day has been calculated. The revenue derived from electricity generation for both CGMPVs and VBFPVs is then analysed under different electricity markets. Actual SE3 2023 spot prices are used as a baseline. To evaluate the impact of a market with higher penetration of solar power, the production profiles from the model *Örebro* were combined with a 2050 prevision of the spot prices from the Spanish bidding zone ES3. This zone represents a scenario with solar cannibalisation, leading to lower prices during peak hours and relatively higher prices during the morning and afternoon - market conditions more favourable for VBFPVs. This allows for a comparative assessment of revenue potential under varying electricity price dynamics.

Finally, in order to validate the predicted production of the model, the production of an existing pilot VBFPV farm project in Kärrbo (59°33'14.4"N 16°45'10.8"E) is also calculated using the model and then compared to actual production data. Though this dataset is incomplete and lacking 28 days of data so conclusion might not be entirely reliable. A summarised list of numerical figures used for the model can be found in Appendix D.

4 Results

The results are first given in terms of the qualitative assessment of Farmer's perspective followed by the quantitative assessment of an APV system. The qualitative assessment provides an answer to the third research question and sets the stage for the quantitative assessment which answers the first and the second objectives.

4.1 Qualitative Assessment of Farmers' Perspective

The interviews provide valuable qualitative insights into the opinions on the application of solar photovoltaic systems and agrivoltaic practices in agricultural settings. The integration of APV with crop production is met with overall caution. Farmers largely oppose the use of arable land for solar installations due to concerns about reduced productivity and potential conflicts with food security goals. While noting that partial shading from solar panels might support certain crops in hot climates, the consensus is that crop-focused APVs are less desirable in regions like Sweden, with limited arable land.

APV is considered suitable for grazing or marginal land applications. One of the farmers observed an increase in crop yield beneath the PV panels due to reduced frost during spring, which enabled the grass to begin growing earlier. The participants emphasized that maximizing land-use efficiency while protecting high-quality agricultural land remains a priority. As one farmer put it, "Using the best farmland for solar installations should be the last option, given the importance of maintaining land for food production."

Agrivoltaic systems integrating livestock were viewed as a promising solution for dual land use, with sheep emerging as a particularly favoured species. A particular benefit that was mentioned was the shade provided to both sheep and vegetation below it. The farmers noted that agrivoltaic grazing can be particularly effective on low-productivity grazing lands. However, it was also noted the management of livestock under APV systems requires careful consideration. One farmer emphasized the need for rotational grazing to maintain vegetation health and to prevent issues such as parasite build-up. Suggestions were also made to expand APV to other livestock, such as pigs and poultry, with appropriate adaptations. Despite potential advantages, farmers noted that integrating larger livestock, such as cattle, may present challenges due to space and infrastructure demands. The economic feasibility of such systems depends on minimizing productivity losses while maintaining the overall health of the grazing ecosystem.

The overall theme among participants was to prioritize marginal or underutilized land, such as grazing areas or uncultivable land, for solar PV systems rather than prime arable land. Farmers expressed concern about potential conflicts between solar installations and the preservation of high-quality farmland for food production.

4.2 Quantitative assessment of an APV system

The results of the quantitative assessment of the APV system are presented in two parts. The first part shows model results for energy generation in CGMPV and VBFPV configurations, followed by a comparison of their feasibility using the LER and economic viability in a solar-dependent energy system. The second part focuses on model verification, comparing outputs with real-world data from the Kärrbo site.

4.2.1 Model results

The production from the CGMPVs reaches its highest levels in the middle of the day, following a bell-shaped curve. In contrast, the VBFPVs generates more output during the morning and afternoon, with reduced production in the middle of the day, as illustrated in Figure 3.

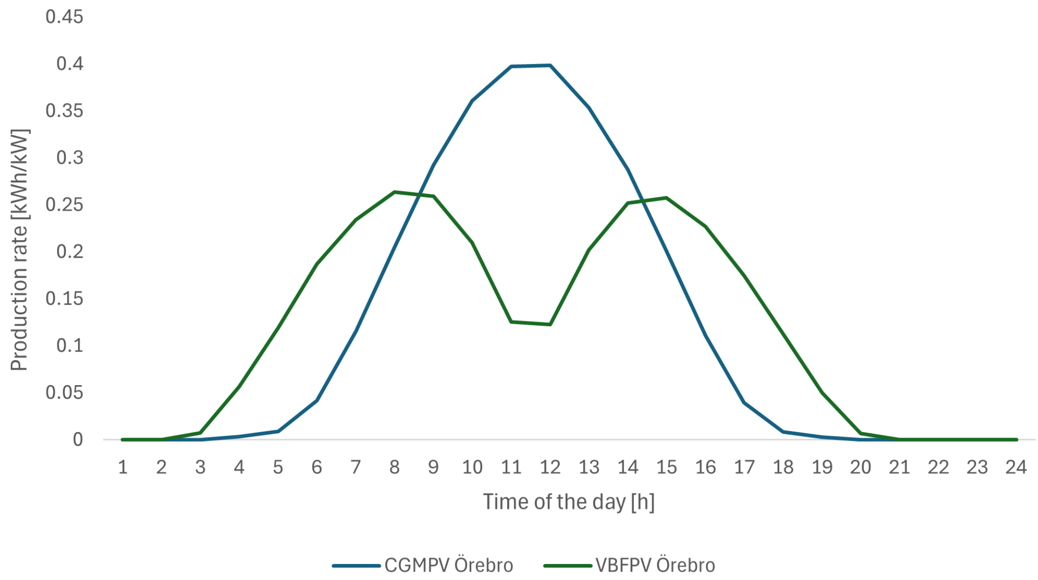


Figure 3: *Production profile for CGMPV and VBFPV of the model Örebro. Daily profile based on a yearly average*

The total electricity production throughout the year 2023 in the model *Örebro* is 10.3 GWh for CGMPVs and 6.6 GWh for VBFPVs, based on a 10-hectare area fully covered with either CGMPVs or VBFPVs. In an electricity market like SE3, without large amplitudes in the electricity price variations, more generation grants also higher revenues. This, together with lower investment costs, makes the installation of CGMPVs over the entire area the most profitable option, as shown also in Figure 4.

The profits coming from sheep grazing is not substantial enough to compensate the higher costs and lower production in Scenario 2, implementing VBFPVs, but is relevant since it makes Scenario 1 more profitable than Scenario 3.

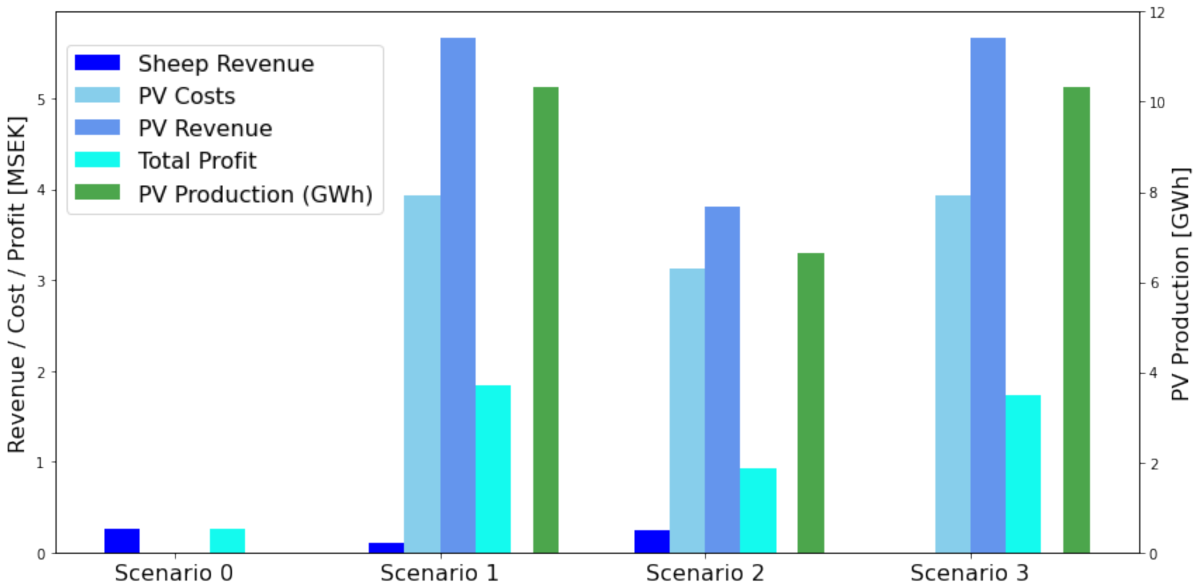


Figure 4: *Scenario comparison between sheep profit, PV cost, PV revenue, total profit and PV energy generation per year*

The calculation of the LER in the four scenarios provides the results shown in Figure 5, with Scenario 2 being the more efficient in terms of dual-use of the land. This outcome is due to the VBFPV installation producing only 36% less electricity than the CGMPV one, while hosting a 1.4 times larger sheep herd. Scenario 0 and 3 can be considered edge cases, with full-agriculture and full-energy land use.

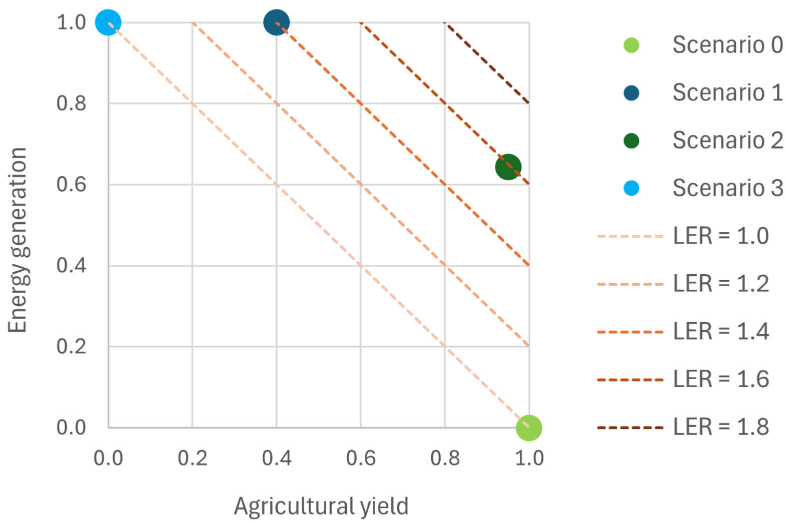
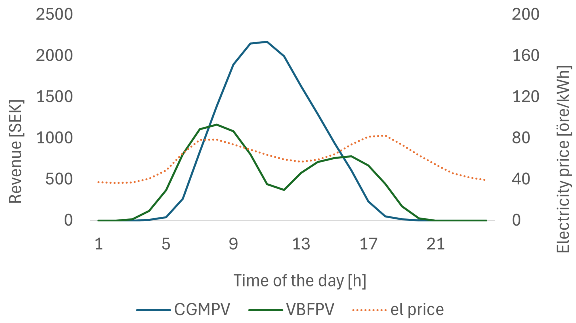
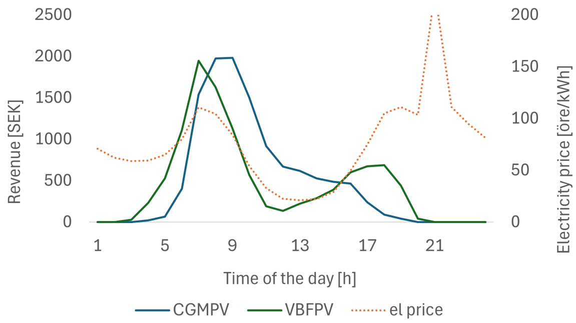


Figure 5: *Land Equivalence Ratio for the four different scenarios*

The effects of the different production pattern during the day between CGMPVs and VBFPVs, shown in Figure 3, can be further evaluated with a revenue comparison, tested in electricity markets with different solar penetrations, as reported in Figure 6.



(a) *Electricity price area SE3*



(b) *Electricity price area ES3 2050*

Figure 6: *Comparison of the revenue from the same electricity production profile of the model Örebro in different electricity markets. Daily profile based on a yearly average.*

On the left graph, one can observe the average daily revenue for both types of panel and the average electricity spot price in SE3, while on the right, one can see the effect of the Spanish prices on the revenue with respect to the same production data.

Table 1: *Yearly revenue of the 2 technologies in different electricity markets*

	CGMPVs	**VBFPVs**
Prices from SE3	5.67 million SEK	3.81 million SEK
Prices from ES3 2050	4.22 million SEK	3.96 million SEK

Comparing the yearly revenue in Table 1, the revenue for the CGMPV installation is still higher than for the VBFPV in both scenarios. Even though, as seen in Figure 6a, the VBFPVs demonstrate a higher capture rate due to the electricity price correlating with its production curve, the total production being significantly lower than that of the CGMPVs. As a result, the total revenue is also lower. Moreover, while the yearly revenue for CGMPVs decreases when using the Spanish spot prices the revenue of the VBFPVs increases when the prices from ES3 are considered. Which well illustrates that VBFPVs are more suited in a high solar penetration market.

4.2.2 Verification of the model

To verify the production data the calculation was carried out for a second site in Kärrbo where Mälardalen University has a test installation. The comparison between the production as recorded at the test site and the output of the model can be seen in Figure 7

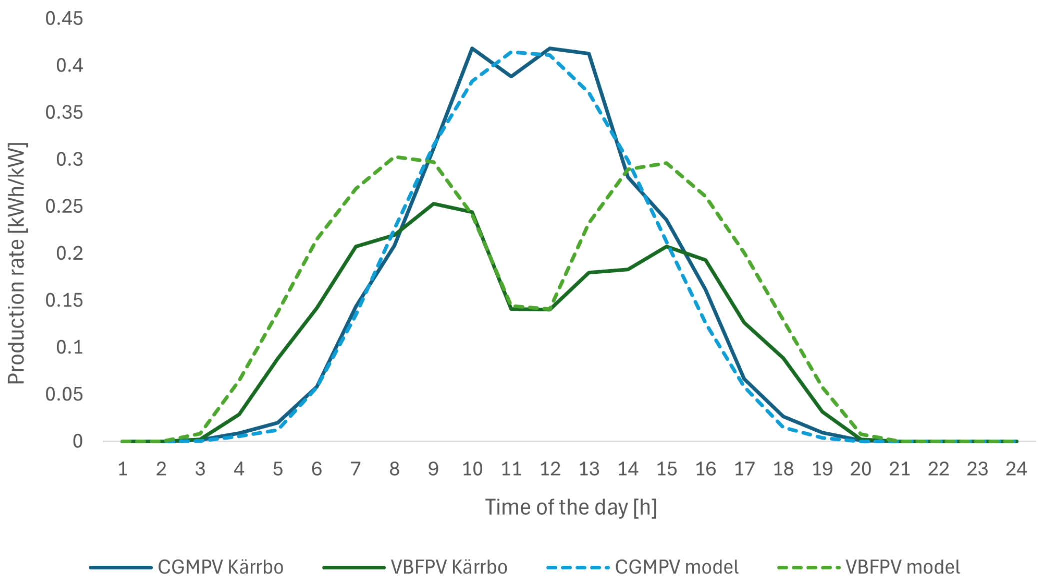
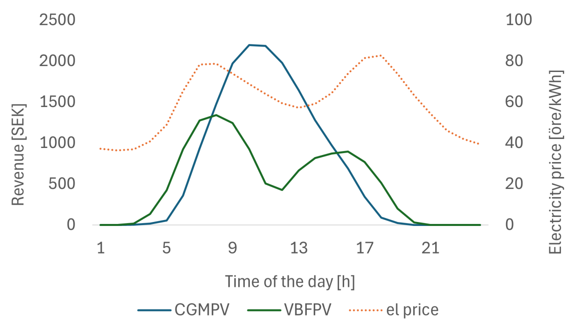
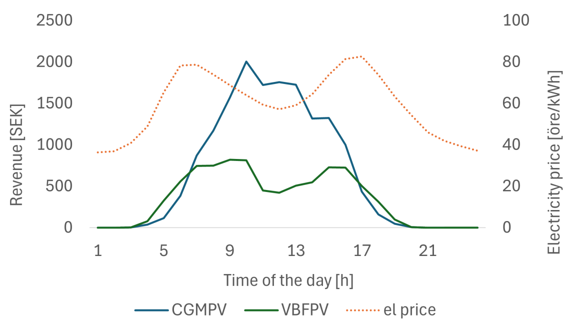


Figure 7: *Production profile for CGMPV and VBFPV models and real data in Kärrbo. Daily profile based on a yearly average*

Figure 7 shows a near perfect correlation between the model output and the actual production observed for the CGMPV installation. This does not hold true for the VBFPV installation, where a slightly higher production was predicted than was achieved. The observed deviation is particularly high during the morning and afternoon where the shading between different panels is expected to be particularly high.



(a) *Model results*



(b) *Real data*

Figure 8: *Comparison of the revenue from electricity production in the Kärrbo model and real data, with prices from SE3. Daily profile based on a yearly average*

To study the effect this deviation has on the revenue prediction, the revenues of the model with either the real data or the predicted production data are shown in Figure 8. The model projects a total revenue of 5.92 million SEK for CGMPVs and 4.38 million SEK for VBFPVs in the Kärrbo. When using the real production data, one ends up with revenues equal to 5.72 million SEK for CGMPVs and 3.07 million SEK for VBFPVs.

A difference in terms of revenue of 4% for CGMPVs and 30% for VBFPVs is observed.

The significant gap between actual and projected revenues for VBFPVs can be explained by several factors. First, 28 days of actual data from Kärrbo were missing, resulting in a corresponding 28-day loss of revenue. The model did not account for such an extended production shutdown. Furthermore, the actual production curve appears lower in the morning compared to the projected one, possibly due to unexpected shading effects not accounted for in the simulation. These effects also contribute to a slight reduction in revenue.

5 Discussion

Considering the model for the quantitative assessment, it is important to discuss the reliability of the power calculator PVGIS tool. One factor of uncertainty is the irradiation database used for the model, as the irradiation is only ever considered per hour, though this effect is mitigated by the ERA5 database used, which tries to estimate the hourly average irradiation. Also, the tool is not designed to estimate production from bifacial panels and, therefore, does not take into account diffuse production from the backsides of the panels. The model attempts to counteract this by modelling a bifacial panels as two monofacial panels, though whether this is sufficient and correct can not be empirically proven without further study outside the scope and time constraint of this report.

The verification of the model also reveals certain flaws within it. Particularly the differences in real production and expected production in the morning and afternoon show the effect that shading between the rows of modules in an installation has. This shading has not been considered in this report. Additionally, the data for the VBFPV installation in Kärrbo lacks 28 days of data due to hardware faults. This makes the comparison less reliable and only allows less confident statements about the reliability of the prediction model.

In a broader sense the selected scope of the model also has to be discussed. As shown in subsection 2.3 the Swedish agricultural sector not only consists of livestock grazing, but also crop cultivation. On the one hand, PV systems can enhance yields by offering partial shading that protects crops from excessive heat or frost. On the other hand, crop performance is influenced by climate and specific conditions, and data on the effects under Swedish climate conditions is sparse. The model used in this project addresses only a limited aspect of the topic. However, it can still be considered a valid example for its intended purpose, as the interviews with farmers in subsection 4.1 indicate that many view livestock grazing, particularly by sheep, as the most suitable option for coexistence with photovoltaic power production. Yet the selection of farmers is rather low and might be biased as they were primarily reached through personal contacts, or individuals already involved with PV systems, representing only a subset of Swedish farmers.

With a larger sample of respondents, it could also be possible to collect enough information to integrate a statistical analysis in the report. Despite the possible bias of the farmers, though, the economic benefits seen in subsection 4.2 still indicate that the practice of sheep grazing combined with photovoltaics is feasible.

In subsection 4.2 the revenue generated from sheep grazing under PV installations is comparatively low to the income from photovoltaic energy production. Additionally the number of sheep per hectare in CGMPV systems ranging from 8 to 20, depending on the specific characteristics of the land and the grazing management practices employed. While sheep grazing contributes to maintaining vegetation under the panels and provides an additional revenue stream, it constitutes only a small fraction of the total revenue generated from the land.

Thus, the dual-use of the land introduces a complex dilemma: the profitability of electricity generation exceeds that of traditional agricultural sheep grazing in Sweden and implementation of these agrivoltaic systems impact the agricultural output. Farming in Sweden presents significant challenges, particularly when compared to other European countries with differing legal frameworks, subsidies, and production costs. Swedish farmers often operate under stricter environmental regulations, which, while essential for sustainability, can reduce their competitiveness in the global market. This economic strain makes it increasingly difficult for farmers to sustain profitable operations, particularly in a climate where global markets favour lowest-cost producers. In this context, the potential economic benefits of a system primarily focused on electricity production could encourage farmers to either lease their land for solar installations or invest in solar energy themselves to sell to the grid, offering a new and potentially more stable source of income. However, this assumes manageable costs for grid connection, which can be significant if the location is remote, a factor that has not been fully accounted for in the pricing considerations. Still, the percentage of land without an easy access to the power grid is only likely to decreases, so there is a risk that some farmers could prioritise energy production over food cultivation, effectively transitioning from agricultural producers to energy providers. Such a shift carries potential consequences for Sweden's food security. The country is already heavily reliant on food imports, and further reductions in the number of active farmers will likely increase this dependency. A continuation of the decline in farming activities might reduce Sweden's capacity to respond to global disruptions, such as those caused by geopolitical conflicts or climate change. Thus, a certain amount of moderation is needed to balance the needs of both the farmers and the demand of a more sustainable energy generation.

When considering an energy system transitioning towards sustainability, new technologies and concepts become increasingly important. For example, installations of east-west oriented VBFPVs can become relevant in an electricity system with a higher share of solar production capacity, thanks to its potential in smoothening the daily variations that characterise solar power. Additionally, the comparison of profits from exporting to a market with the prices of the 2050 ES3 bidding zone illustrates how profits depend on the market and, consequently, on the availability of cheap production capacity throughout the day. With a higher installed capacity of conventional PV, as the case in Spain, the profit of CGMPV installations may very well sink. On the other hand, the same effect has a positive impact on VBFPV installations. Depending on the market outlook, stakeholders may thus favour unconventional installations to have a more stable profit expectation.

6 Conclusion

APVs represent a promising approach to simultaneously address the challenges of renewable energy production and sustainable agriculture. By integrating photovoltaic technology with agricultural practices, APVs have the potential to optimize land use efficiency, generate additional revenue streams for farmers, and mitigate the effects of climate change.

In the Swedish context, APVs offer distinct advantages, particularly for livestock grazing or utilising marginal lands. The adaptability of technologies like VBFPV ensures minimal disruption to agricultural productivity while supporting energy generation. However, challenges such as low sunlight availability, higher initial investment costs, and the need for customised designs to suit Sweden's unique climate conditions must be addressed.

The qualitative assessment highlighted cautious optimism regarding the integration of APVs, with a strong preference for prioritizing marginal lands over prime arable land. Stakeholders emphasized the importance of balancing food security with energy goals and suggested that careful planning and innovative designs are essential for the long-term sustainability of APVs.

The quantitive assessment demonstrated that while CGMPV systems are currently more profitable due to their higher energy yield, VBFPV provides a compelling case for integration in certain contexts. As solar market dynamics evolve and land-use pressures intensify, VBFPV may play a more important role.

Looking ahead, the widespread adoption of APVs in Sweden will require a supportive regulatory framework, continued technological innovation and active engagement with farmers and local communities. With careful implementation, APVs can contribute to tome extent to Sweden's goals of achieving a sustainable energy transition and bolstering its agricultural resilience in a changing global landscape.

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Appendix

A List of agrivoltaic installations

Table 2: *Overview of Agrivoltaic Projects in Sweden [37]*

State	Location	Capacity [MW]	In Operation	Animal
Skåne	Forsby	3	2022	Sheep
Skåne	Sjöbo	18	2019, expanded 2021	Sheep
Skåne	Åhus	7.2	2022	Sheep
Skåne	Vinslöv	0.5 ha	2014	Horses
Västra Götaland	Uddevalla	0.253	2018	Sheep
Sörmland	Strängnäs	21	2020, expanded 2023	Sheep
Västmanland	Kungsåra	22	2023	Sheep
Örebro	Torphyttan	0.502	2020	Sheep
Norrbotten	Luleå	0.699	2020	Sheep
Örebro	Vässlingby	0.635	2023	Grass
Västmanland	Kärrbo	0.0118 (CGMPV)/ 0.0228 (VBFPV)	2021	Ley grass,barley
Västra Götaland	Hova	8 GWh/year	2024	Rapeseed, wheat, pasture
Kalmar	Törneby Solpark	3 MWh/year	2018	Grass

B Derivation of sheep value

$$Sheep_{2010}\,[SEK] = \frac{profit_{farm_1} + profit_{farm_2}}{2} \tag{2}$$

$$Sheep_{2024}\,[SEK] = (CPI_{2010} + 0.8 \cdot (CPI_{2024} - CPI_{2010}) \cdot Sheep_{2010} \tag{3}$$

The profit per sheep has is calculated by taking the average value of two farms, Equation 2, from 2010 adjusted to 2024 using consumer Price Index (CPI), Equation 3, 80% of the indexation are assumed to be the increase in profit for the Sheep.

Table 3: *Revenue, Costs and profit for Sheep Farming (2010, SEK)[38]*

Item	Farm 1 (SEK)	Farm 2 (SEK)
Revenue		
Slaughter animals & wool	930	1,650
Additional revenue from livestock & skin sales	310	100
Increased livestock capital minus purchased animals	200	
Environmental & compensation subsidies	680	920
Farm support	420	350
Costs		
Feed cultivation excl. machinery costs	-160	-290
Machinery incl. fuel & hired machine work	-420	-520
Purchased feed	-110	-750
Buildings	-90	-220
Interest on livestock & working capital	-120	-100
Other costs	-390	-340
Revenue − Costs = Compensation for labor & land = profit	1,050	990

Table 4: *Sheep Profit and CPI (2010 and 2024)*

Year	2010	2024	2024 - 80%
Sheep profit (SEK)	1,020	1,397	1,322
CPI Sweden [39]	302	413.75	

C Model description

The analysis of the profitability of each scenario is based on Equation 4

$$Profit\ [SEK/year] = P_{sheep} - I_{PV} - O\&M_{PV} + R_{PV} \tag{4}$$

P_{sheep} is the profit from sheep farming, calculated as follows:

- The herd size in each scenario is derived from the number of sheep per hectare and land size (Appendix D).
- The profit is calculated as product of herd size and sheep value [SEK/sheep/year] (Appendix B and D). The profit is expressed in SEK/year.

I_{PV} and $O\&M_{PV}$ are the annualised capital cost (CAPEX) and operational cost (OPEX) respectively from the PV installation, calculated as follows:

- The annualised CAPEX is derived from total CAPEX with the annuity formula (Equation 5)

$$I_{PV}\ [SEK/year] = CAPEX_{PV} * \frac{r}{1-(1+r)^{-n}} \tag{5}$$

  - $CAPEX_{PV}$ is calculated as product of investment cost [SEK/kWp], installed capacity [kWp/ha] and land size [ha] (Appendix D).
  - r and n are respectively the interest rate and the lifetime of the PV installations (Appendix D).
- The OPEX value is considered to be 0.75% of the annualised CAPEX value.

R_{PV} is the revenue from electricity generation, calculated as follows:

- The hourly production data for the entire year for both CGMPVs and VBFPVs are derived from the PVGIS ERA5 database for an installation size of 1000kWp at the coordinates 59°00'00"N 15°00'00"E. The values derived from this are an hourly timeseries of production in Wh/h for every hour of the year in UTC time [40][36].
  - For the CGMPV system a south facing installation with 45° tilt are used as input for PVGIS
  - For the VBFPV system the production data for an east facing and a west facing installation each with the named peak capacity and a 90° tilt are derived from PVGIS and summed together
  - The values derived from PVGIS are converted to kWh/kWp for further calculations, taking into account a PV system efficiency of 87% (Appendix D).
  - In the case of Kärrbo, the same method is followed but for the coordinates 59°33'14.4"N 16°45'10.8"E.
- Silvia Ma Lu at Mälardalen University was kind enough to provide the authors of this report with the measured production data of their test site in Kärrbo for the year 2023.
- The hourly electricity prices for the entire year in the SE3 price area are taken from the ENTSO-E database [41]. The prices are expressed in EUR/MWh for every hour in UTC time.
  - The values are converted into SEK/kWh, taking into account a currency exchange of 1 EUR = 11.5 SEK.

  - In the case of ES3, the values are derived from material of the course *SEE030 Variation management in the electricity system*, examined by Lisa Göransson.

- The electricity generation of CGMPV and VBFPV installations are calculated as a product of the specific production profiles [kWh/kW] and installed capacity [kWp] of the two technologies. The values are expressed in kWh/h.

  - The total yearly generation of CGMPVs and VBFPVs are obtained as sum of all hourly values. The unit then becomes kWh/year.

- The revenues of CGMPV and VBFPV installations are calculated as a product of the electricity generation [kWh/h] of the two technologies and the electricity price profile [SEK/kWh]. Values are expressed in SEK/h.

  - The total yearly revenue of CGMPVs and VBFPVs are obtained as sum of all hourly values. The revenue is expressed in SEK/year.

D Overview of figures used in model

Figure	**Value**	**Reference**	**Comment**
sheep/ha (pasture)	20	Hushållnings-sällskapet [23]	It is assumend to be cultivated land and thus one derives a figure of 20 tackor from the guideline
sheep/ha (CGMPV)	8	Stridh et al. [34], Hushållnings-sällskapet [23]	40% of sheep grazing capacity of normal pasture. The value is derived from the reduction of metabolic crop yield presented in Stridh et al. [34]
sheep/ha (VBFPV)	19	Stridh et al. [34], Hushållnings-sällskapet [23]	95% of sheep grazing capacity of normal pasture. The value is also derived from the reduction of metabolic crop yield presented in Stridh et al. [34]
kWp/ha (CGMPV)	1000	Kraftringen [42]	Capacity of the agrivoltaic installation in Forsby
kWp/ha (VBFPV)	635	Linde Energi [35]	capacity of the pilot project Solvallen near Västlingby
profit /sheep/year	1300 SEK	Appendix B	See derivation in Appendix
investment cost/kWp (CGMPV)	6000 SEK	Westerberg et al. [43]	Using the figure of Small centralised PV with 1-20MWp and assuming a price decrease for the coming year as is also discussed and projected in the survey
investment cost/kWp (VBFPV)	7000 SEK	Westerberg et al. [43], expert interview [13]	It is assumed that about 20 percent of CGMPV installation costs are related to the mounting structure, while for VBFPV it is closer to 32 percent
system efficiency	87%	PVGIS [40]	Typical system performance used by the PVGIS tool
lifetime PV	30 years	Stucki et al. [44]	typical figure used in LCA
interest rate	6%	Westerberg et al. [43]	

E Interviews

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Farmer 1

Type of Farmer: Dairy farming, meat production, and forestry.

Solar Installations:

- Planned installation of a 35-hectare solar farm on leased forest land (10 ha clear-cut, 25 ha mature forest).
- Lease period: 40 years.
- Timeline: Expected start by 2027, pending grid connection approval.

General Thoughts on Solar PV:

- Negative, citing inefficiency due to simultaneous electricity generation across installations.
- Believes solar panels are not currently cost-effective.

Thoughts on Agrivoltaics:

- Not supportive on arable land.
- Potential for use with sheep grazing.

Farmer 2

Type of Farmer: Dairy farming (milk production).

Solar Installations:

- Solar panels on the roof of their barn.

General Thoughts on Solar PV:

- Positive for environmental benefits and farming economics.
- Stresses the importance of avoiding competition with high-quality farmland.

Thoughts on Agrivoltaics:

- Supportive if combined with animals such as pigs, hens, or sheep.

- Suggests raising panels for better integration with livestock.

Farmer 3

Type of Farmer:

- Dairy farming with 135 cows, KRAV-certified organic farm since 1995.
- Cultivates feed crops, rapeseed, and natural pastures.
- High-tech farm operations, including robotic systems and electric loaders.

Solar Installations:

- 0.6 MW system on the barn roof, part of a cooperative with 113 individuals and six local companies.
- Additional solar farm on grassland shared with sheep grazing, producing 600,000 kWh annually. On this land there are 30 sheep on 4 hectares.

General Thoughts on Solar PV:

- Positive for environmental benefits and farming.
- Believes solar panels should not compete with high-quality farmland.
- Views solar panels as a reversible and low-impact land use.

Thoughts on Agrivoltaics:

- Supports use with grazing sheep, which find shade under the panels beneficial.
- Cautions against installations on high-quality arable land.

Farmer 4

Type of Farmer:

- Mixed organic farming: Grains for human consumption, pigs, cows, sheep, grass, oil crops, beans, natural pastures, and reserves.
- Land size: 500 hectares (50% pasture, 50% arable land).

Solar Installations:

- No current installations.
- Considered solar panels but chose not to proceed, prioritizing vertical panels or less productive land instead.

General Thoughts on Solar PV:

- Positive, emphasizing low maintenance and environmental benefits.
- Prefers installations in forests or on less productive land.
- Highlights ethical conflicts in using prime farmland for solar.

Thoughts on Agrivoltaics:

- Supports use with grazing animals, particularly sheep.
- Warns about risks of biodiversity loss and long-term impacts on soil when grazing under panels over long periods.
- Quote: "Using the best farmland for solar installations should be the last option, given the importance of maintaining land for food production."

Farmer 5

Type of Farmer:

- Regenerative Farming: Focus on enhancing soil health. Raising sheep and cows

Solar Installations:

- One installation, 3MW.

General Thoughts on Solar PV:

- Positive.

Thoughts on Agrivoltaics:

- Supports use with grazing animals, particularly sheep.
- Positive about it, sees benefits for both sheep raising and PV production. Optimizes land use.